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MATERIALS AND FABRICATION STUDIES FOR ADVANCED POLYMER ELECTRO-OPTIC DEVICES

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During the period of this contract, great progress has been made in new electro-optic polymers and in high speed infrared modulators using these polymers. There have been recent significant advances in the synthesis of molecules with large optical nonlinearity which have been sterically designed to prevent large dipole-dipole interactions between the molecules from preventing the alignment of the molecules during electric field poling.

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I. RESEARCH PROGRESS

31. Electro-optic Polymer Materials and High Speed Modulators

During the period of this contract great progress has been made in new electro-optic polymers and in high speed infrared modulators using these polymers. There have been recent significant advances in the synthesis of molecules with large optical nonlinearity which have been sterically designed to prevent the large dipole–dipole interactions between the molecules from preventing the alignment of the molecules during electric field poling. One of the most promising of these, a ring-locked phenyl-tetraene bridged chromophore [1] which has been labeled CLD by Chang and Dalton. This chromophore has been used in a guest–host system of poly-methylmethacrylate (PMMA) to realize an EO coefficient over 85 pm/V at 1060 nm. However, the PMMA host has a relatively low T_g, and does not provide sufficient thermal stability for practical devices. A host polymer is required to have high T_g, good solubility with the CLD molecule, low loss at 1300 and 1550 nm, and compatibility with standard photolithography. It has been particularly difficult to find host polymers with low loss at 1550 nm because, it is believed, of loss due to overtones of C–H vibration. Recently, amorphous polycarbonate [2] (APC) has been identified as a promising host material. The properties of the APC/CLD material along with a demonstration of a Mach–Zehnder (MZ) amplitude modulator with a low driving voltage are discussed in this section.

To determine the optimum poling temperature, we prepared samples of APC/CLD (30 wt. % density) coated on ITO glass. The APC/CLD films were poled at various temperatures for 30 min using corona poling in air (8 kV, 2 cm tip to surface distance). The r_{33} electro-optic coefficient was measured at 1060 nm using the ATR method [3] and is shown in Fig. 1. An EO coefficient of 90 pm/V was achieved at a poling temperature of

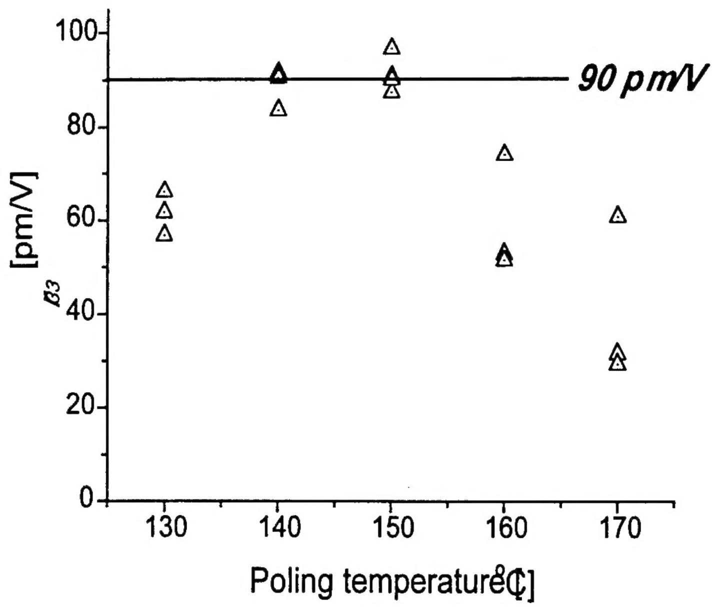


Fig. 1. Electro-optic coefficient of PC/CLD polymer @ 1.06 μm for the different poling temperatures.

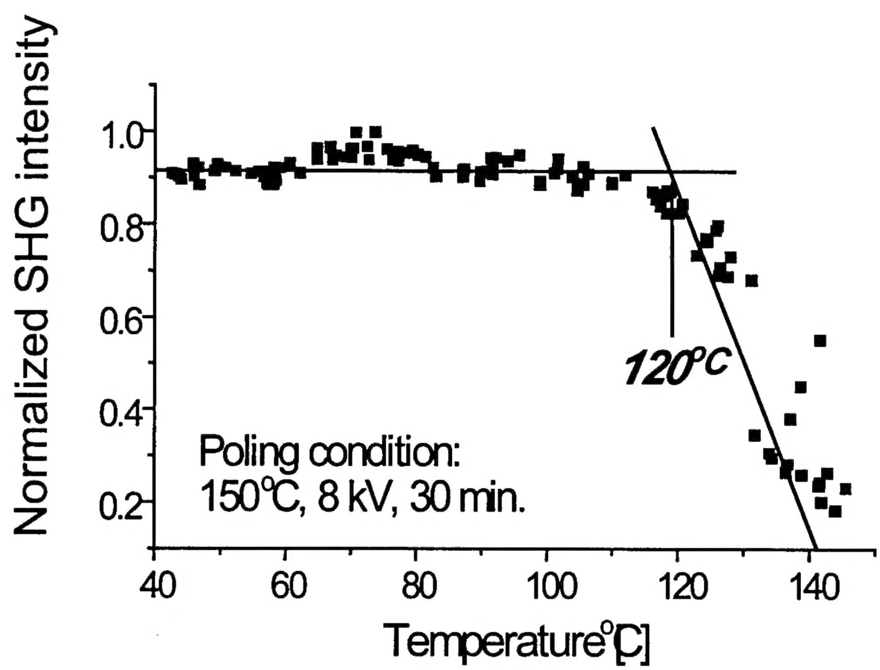


Fig. 2. Thermal stability of PC/CLD polymer measured by an in-situ second harmonic generation.

140–150 °C. Using a two level model for the dispersion of r_{33} (λ_{max} = 670 nm) predicts ~65 pm/V at 1300 nm and ~55 pm/V at 1550 nm. The thermal stability of the poling was measured by the *in situ* second harmonic technique and is shown in Fig. 2. In this measurement, the temperature of the sample to ramped up at a rate of 10 °C/ min. The knee in the data is at ~120 °C which indicates that long term stability can be expected up to approximately 90 °C. Initial measurements of the optical loss were made in a planar waveguide of APC/CLD on a Si substrate with a 4 μm thick oxide layer. The propagation loss was measured by using the high-index liquid immersion technique[4]. It was found to be ~1.2 dB/cm at 1300 nm and ~2.0 dB/cm at 1550 nm. As shown later, the loss at 1550 nm in buried ridge waveguides is lower than this, probably due to the air interface scattering in the planar waveguides.

The APC/CLD material is difficult to process using standard photolithography because the solvent of photoresist damages the film. In order to protect the APC/CLD layer, we coated an additional thin polymer layer of a UV-curable epoxy, UV15, (from Masterbond Co.) on the APC/CLD as shown in Fig. 3. The UV15 was also used for the lower cladding layer (2.5 μm), which was coated on the Au ground plane and cured. After coating the APC/CLD core layer (2.5 μm), the film was corona poled at 150 °C for 30 min by 9 kV. Then, the UV15 solution, diluted with methanol, was coated to make a thin protective layer of about 0.6 μm thickness. The waveguide lines were patterned on the protective layer by standard photolithography Using O_2 reactive ion etching (RIE) the UV15 protective layer was etched to make a rib structure of 0.4 μm height. After the first RIE, the photoresist residue was removed by using a developer. Finally, the waveguide pattern in the UV15 layer was transferred into the APC/CLD layer by the second RIE etch over the entire surface. The rib height of the waveguide became ~0.3 μm

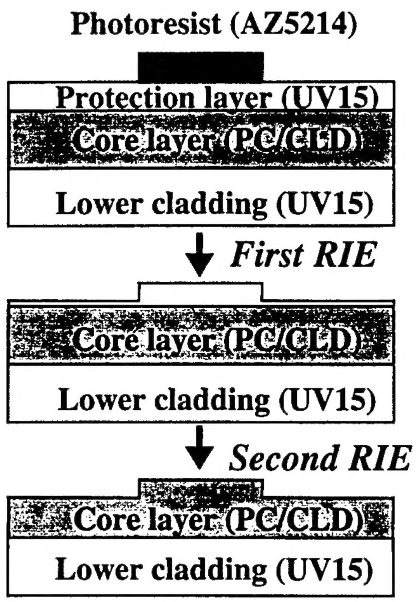


Fig. 3. Two step RIE for PC/CLD polymer waveguide fabrication with the thin protection layer of UV15.

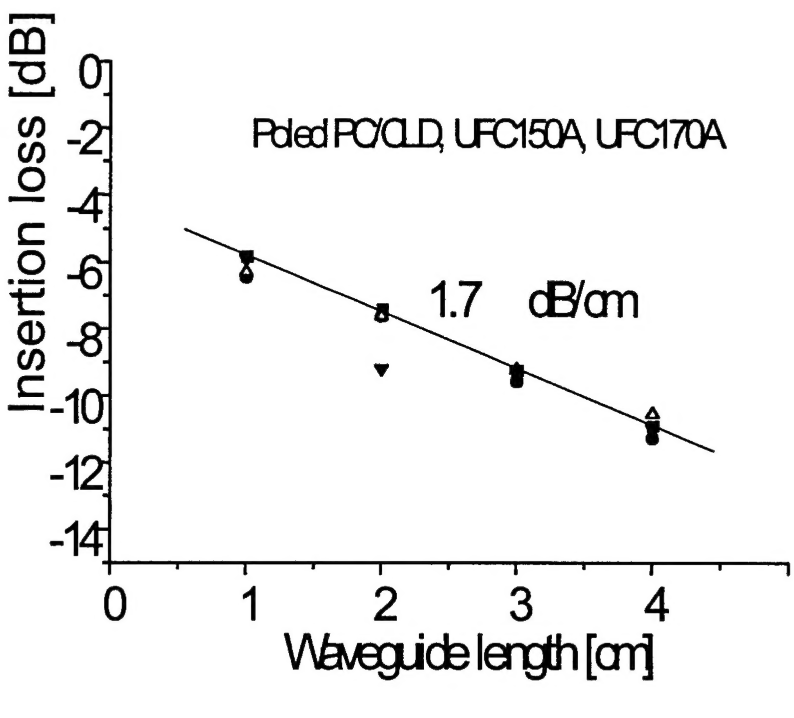


Fig. 4 Waveguide loss @ 1550 nm using the cut-back method

after the second RIE due to the faster etch rate of the UV15 as compared to that of the APC/CLD.

Another UV curable polymer, UFC-170, was used for the upper cladding. [5]. UFC-170 is a specially synthesized acrylic polymer for coating of the APC/CLD layer without dissolving it. It requires a relatively small dosage of UV to cure and gives very hard films after crosslinking. The total thickness of the device became 7.5 μm. The upper micro-strip electrode was deposited and then electro-plating was used to increase the electrode thickness to ~3 μm. The end facet of the waveguide was diced with a nickel blade for light coupling.

The mask for patterning the MZ interferometer also contained straight waveguides and these were used to measure the waveguide loss by the cutback method. As shown in Fig. 4, the data give consistent results with the propagation loss of 1.70 dB/cm at 1550 nm for the transverse magnetic (TM) polarization. The loss for transverse electric (TE) polarization was 1.65 dB/cm. These measurements were made in poled material and we see no significant contribution from poling induced loss [6]. The ridge waveguide loss is less than that measured in the planar waveguide perhaps due to reduced scattering at the core–upper cladding interface compared to that at the core–air interface.

To measure the performance of the MZ modulator, a normal single mode fiber was aligned to couple TM polarized light of 1300 or 1500 nm wavelength into the wave-guide. The output light was focused at a detector by a microscope objective lens. A dc bias was applied to obtain the maximum output power by compensating for the initial phase mismatch of the MZ modulator. At the both wavelengths, the total insertion loss from the fiber output, through the device, and coupled to the detector was measured to be 9–10 dB. From the cutback measurement results, the total device loss in the 3 cm long MZ waveguide is estimated to be ~5 dB. The coupling loss between the fiber and the

waveguide is estimated to be ~3.5 dB due to the significant mode size mismatch and the output coupling loss through the lens is ~0.5 dB.

The low frequency electro-optic modulation response of the device was measured by applying a 1 kHz electrical signal with a saw-tooth wave form. For the MZ modulator, with a 2 cm long electrode, the V_π was measured to be 2.4 V, which corresponds to an r_{33} of 47 pm/V at 1300 nm. At 1500 nm, the V_π was 3.7 V with a corresponding r_{33} of 36 pm/V.

The EO modulation response is shown in Fig. 5. The electro-optic coefficient in the modulators is about 70% of the value predicted from the single layer films. We believe the poling was not as efficient in the modulator due to the difference in electrical conductivity of the core and lower cladding at the poling temperature [7] If a different cladding material with lower resistivity at the poling temperature is used, it should be possible to further decrease the V_π. The extinction ratio of the MZ modulator was greater than 20 dB, which indicates that the waveguide is single mode. To confirm the high frequency operation of the fabricated devices, the optical response was measured using a lightwave component analyzer~HP83420A! from 2 to 20 GHz. In that frequency range, the optical signal dropped by 1.5 dB.

In summary, the state of the art in polymer electo-otics is an EO polymer modulator with an APC/CLD polymer that exhibits a V_π of 2.4 and 3.7 V for 1300 and 1550 nm wavelengths, respectively. The loss of the 3 cm long modulator was ~5 dB (not including the fiber coupling loss) for both wavelengths. Since the velocity mismatch is not an issue in polymer modulators, the 3 dB modulation frequency bandwidth is set by the microwave loss of the microstrip line [8]. In frequency response measurements of the MZ modulator from 2 to 20 GHz, the optical signal dropped by 1.5 dB.

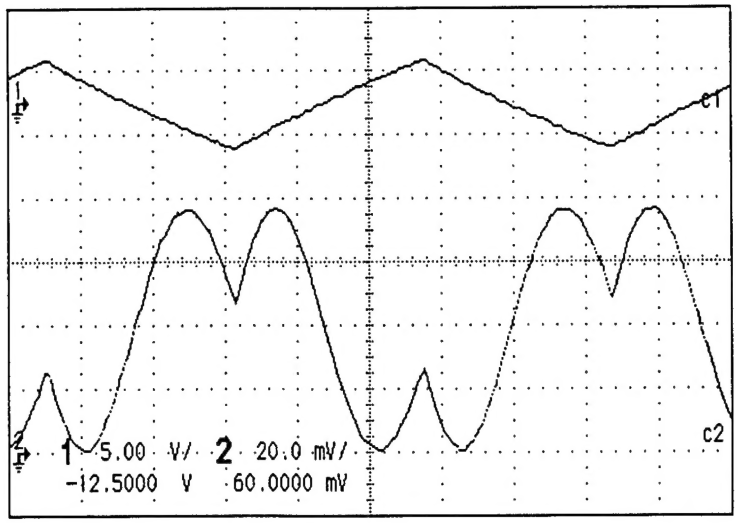


Fig. 5. Electro-optic modulation response of PC/CLD MZ-modulator for the 1.55 μm wavelength exhibiting a V_π of 3.7 V and an extinction ratio over 20

B. Photonically Controlled rf Phase Shifter

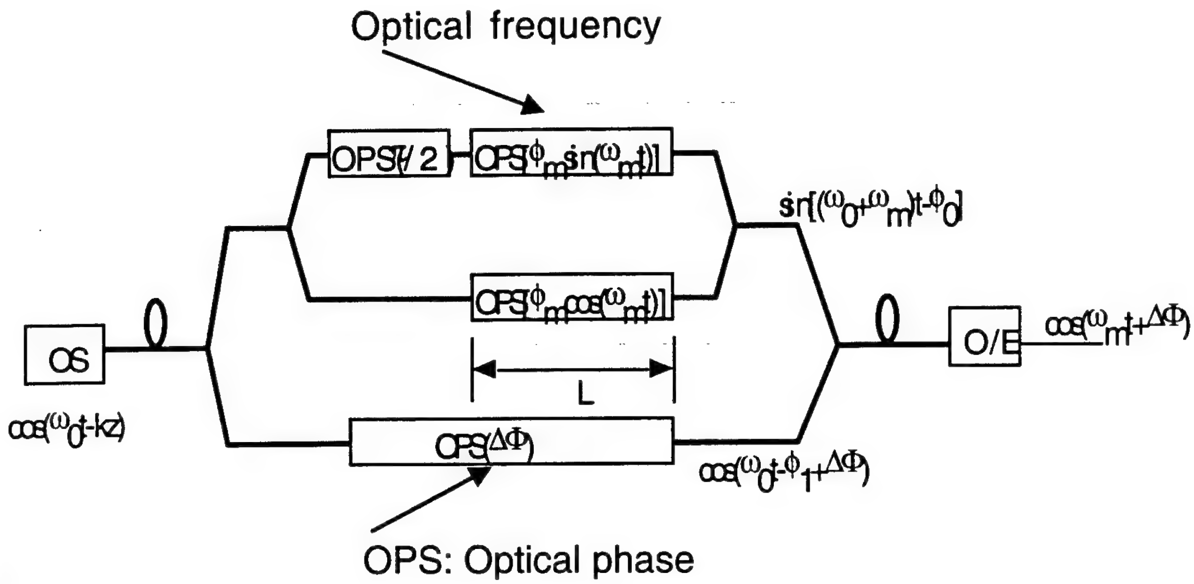
We recently completed, in collaboration with Prof. Harold Fetterman's group at UCLA, a demonstration of the application of electro-optic polymers in an integrated rf photonic phase shifter[9]. One of the key components of an integrated approach to a large photonically contrlled phased array is a photonic RF phase shifter that can provide accurate and easily controllable phase shift.

The basic configuration of our RF phase shifter is shown in Fig. 6. The reader is referred to the 1999 Annual Report for more details. The optical input is a laser field E_{in} at a frequency Ω. The field is assumed to split in the ratio $\alpha:\beta$ at the first Y junction and equally at the second Y junction. The electrodes of the arms 1 and 2 are driven with the in-phase and quadrature components derived from the same microwave source. The RF driving frequency and amplitude are denoted by ω and V_m respectively. An additional optical phase shift θ is introduced in arm 2 using a DC bias. If θ is chosen to be 90°, a single side band (SSB) output is obtained at frequency $(\Omega+\omega)$.

The successful fabrication and testing of the phase shifter further illustrates the maturity and flexibility of the polymer waveguide technology and the possibility of realizing other novel configurations.

C. Fast maskless fabrication of electrooptic polymer devices by simultaneous direct laser writing and electric poling of channel waveguides

The conventional process of fabricating electrooptic (EO) polymer waveguide devices involves electric poling to achieve noncentrosymmetric order and photomasks to define channel waveguides by reactive ion etching or photobleaching. Photomasks add cost and time to the device development, and they limit the flexibility in changing device parameters. To overcome the limitations of photomasks, maskless techniques, such as photopolymerization, electron beam writing, and laser ablation, have been proposed for



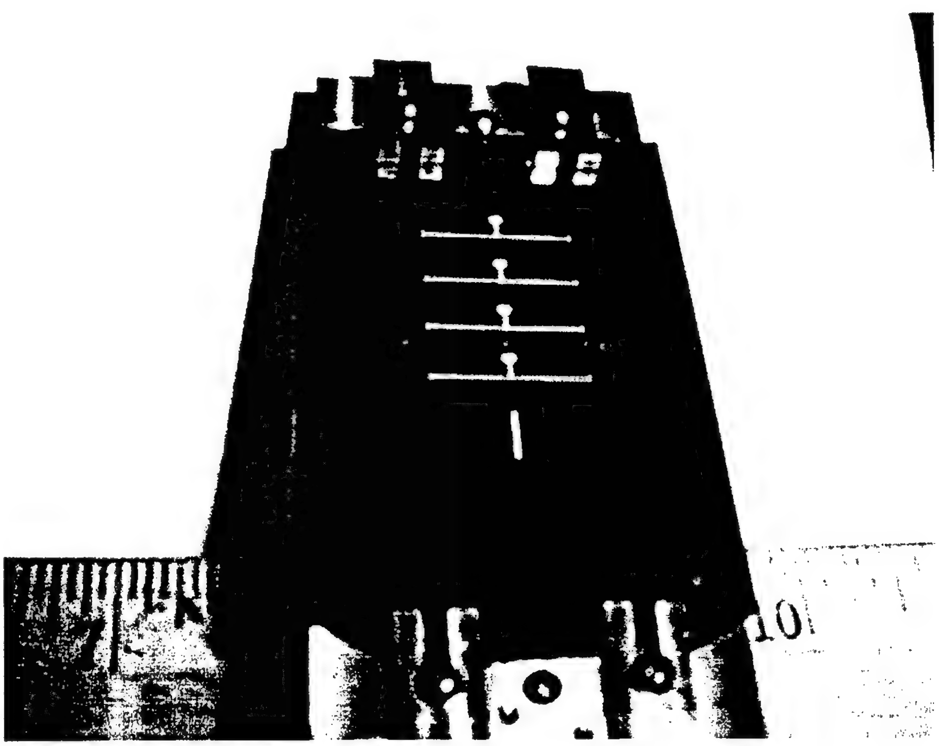


Figure 6. The upper figure shows the schematic of the photonic rf phase shifter. The microwave signals are applied to the arms of the upper Mach Zehnder with a 90° phase shift. The phase of the microwave modulation on the optical carrier is controlled by the dc voltage on the lower electrode. The lower part of the figure shows a photograph of an array of four of the phase shifter fabricated using EO polymers.

fabricating channel waveguides in polymer thin films. However, these techniques are restricted to passive waveguides since the temperature involved destroys the EO effect by randomizing the poling order of active molecules. During this contract period, we have demonstrated a novel but simple technique of simultaneous direct laser writing and electric poling of arbitrary channel waveguides that have EO properties. This technique can be very useful for the fast prototyping of active devices such as modulators and switches.

The principle of this method is shown in Fig. 7. The sample to be written with channel waveguides consists a substrate, gold ground electrode, three spun layers of polymer (upper and lower passive cladding and active core), and a semi transparent upper electrode. For fiber coupling, the endfaces of the sample are either cleaved or cut with a dicing saw before waveguide writing. The core layer that we used is a disperse red 19 (DR19) containing polymer. The absorption peak of the DR19 chromophores is at 470 nm. Waveguide writing is made with a focused beam of 488 or 515 nm from a cw Ar^+ laser. When the beam scans in the xy plane across the sample without applying the poling voltage or in the area outside the top electrode, the chromophores in the path of the beam are preferentially aligned along the Z direction with, on average, equal number of chromophore dipoles pointing up and down due to photo-orientation. The partial alignment parallel to the Z axis increases the refractive index for TM polarization and a passive channel waveguide that only supports the TM mode is made. When the laser beam scans across the area with top electrode and a poling voltage is applied, the chromophores are preferentially aligned with its chromophore dipoles in -Z direction due to a process known as light assisted electric poling [10]. An electrooptic channel waveguide is formed.

For more details the reader is referred to the 1998 Annual Report.

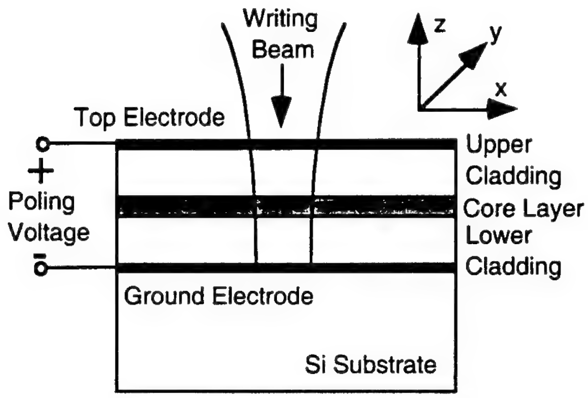


Fig. 7 Principle of the waveguide writing and poling.

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